Mirror Technology Roadmap for NASA's Exoplanet Exploration Program

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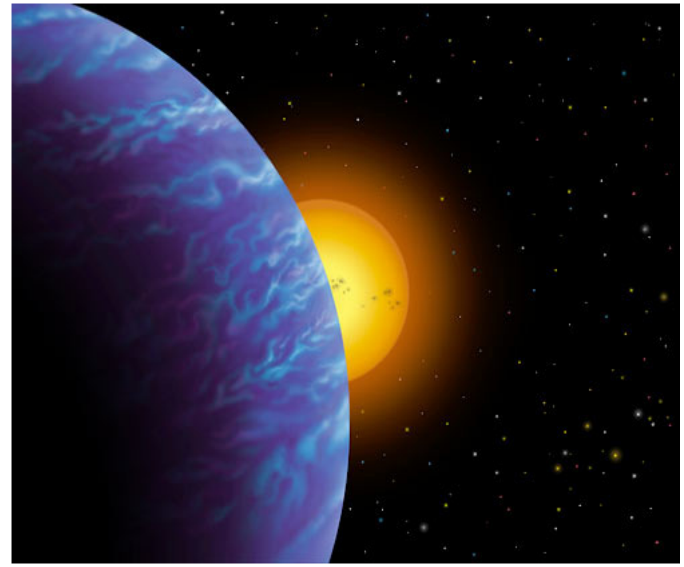
Exoplanet Science Goals

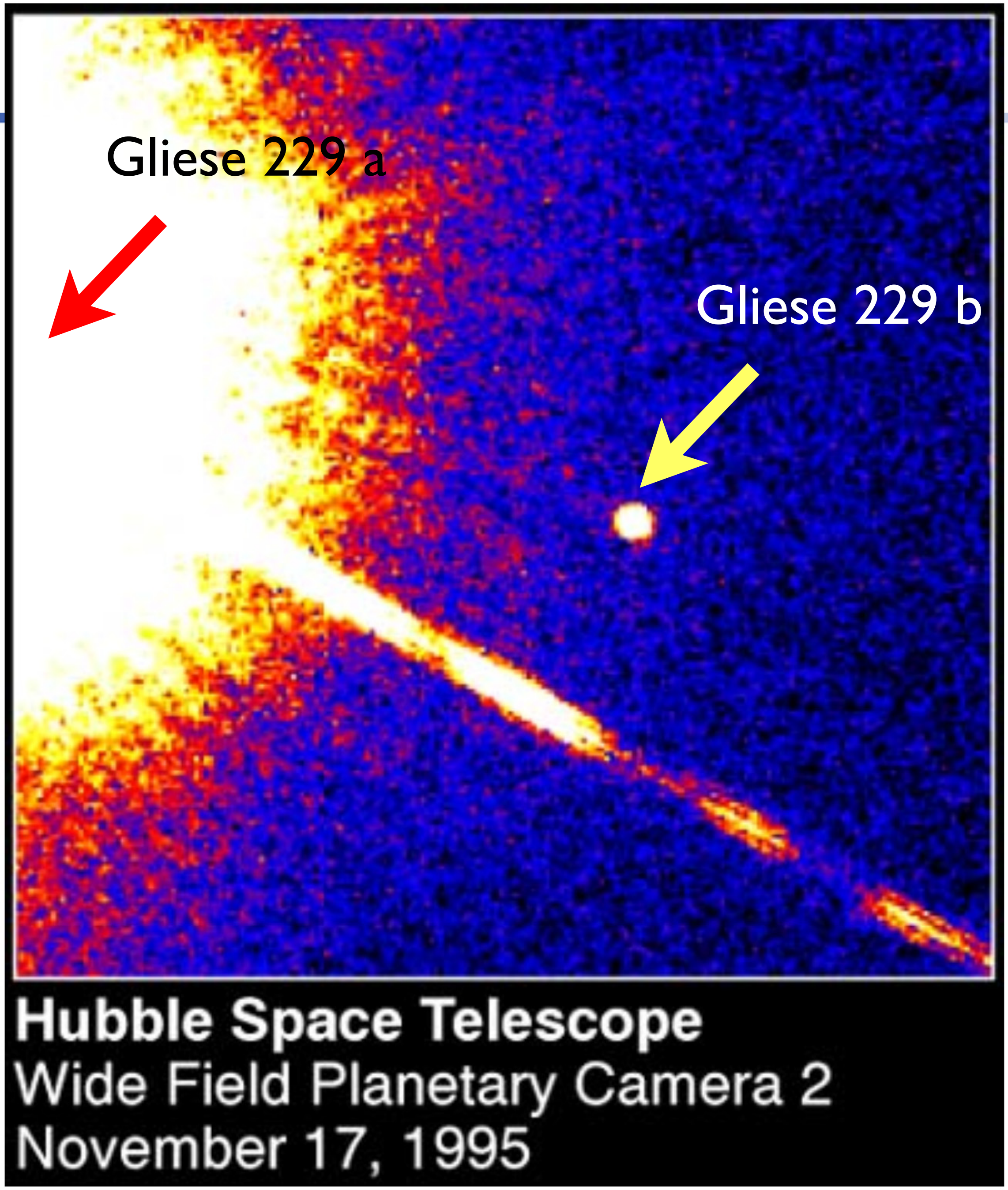
ExoPlanet Exploration Program

- Direct detection of terrestrial planets in the habitable zone around nearby stars
- Characterization of planetary atmospheres in search of the signatures of life
- Direct detection and characterization of other constituents of planetary systems
- Revolutionary general astrophysics investigations



- **Direct detection** - *must separate planet light from star light*
- **Planet characterization** - *must determine type of planet, its gross physical properties and atmosphere constituents* allowing *assessment of likelihood of life*

ExoPlanet Exploration Program



Brown Dwarf
44 AU
20-50 M_J

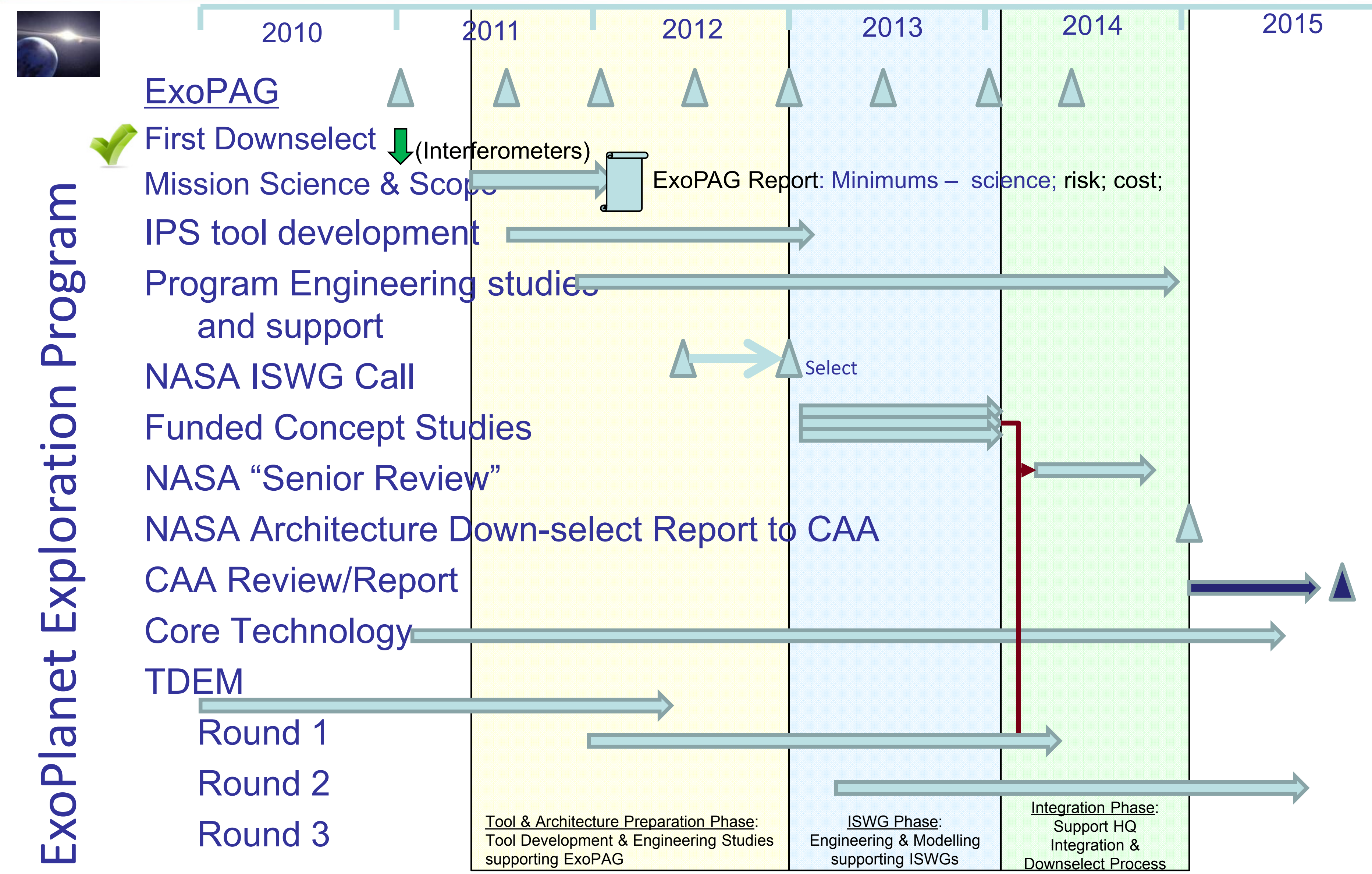
Discovered
1995

Starlight suppression allows the *spectra* of planets to be detected

2.4-m telescope

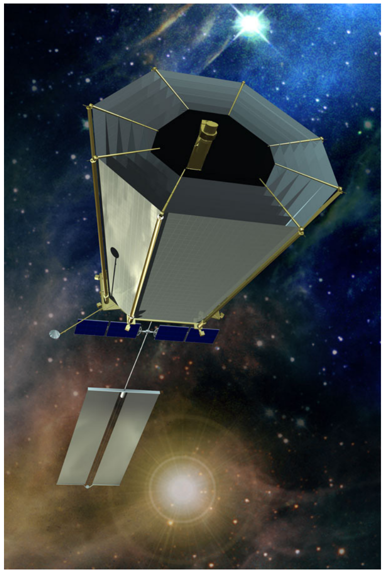
50 mas resolution

A 5-Year Horizon

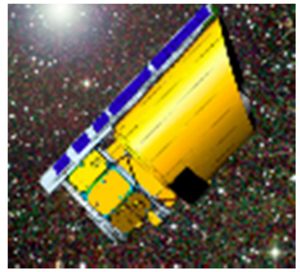


Rogues Gallery of Exoplanet Mission Concepts

ExoPlanet Exploration Program



TPF-C Terrestrial Planet Finder Coronagraph



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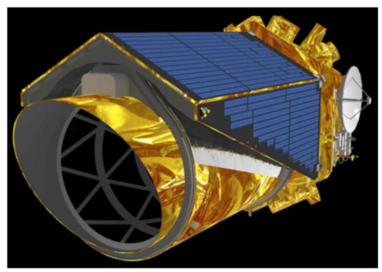

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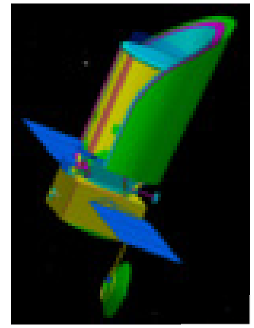

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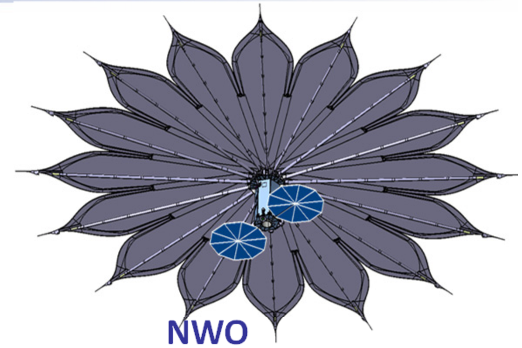

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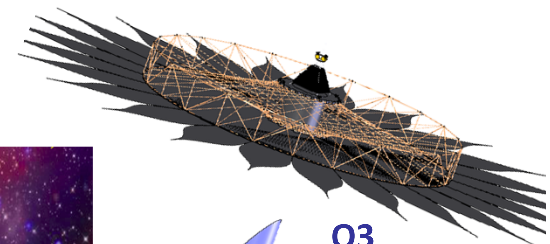
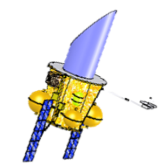
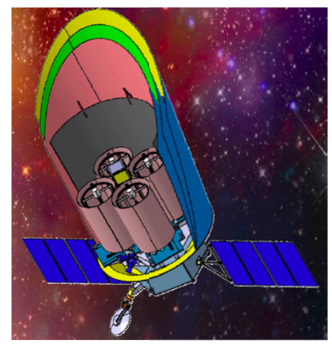
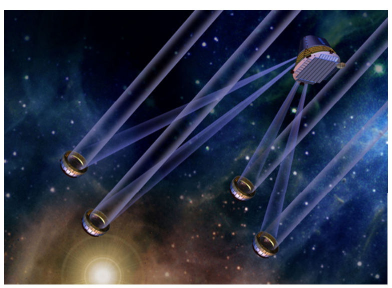




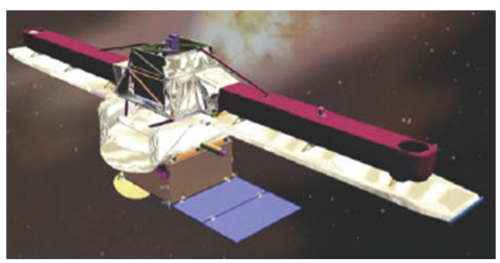
O3 Occulting Ozone Observatory



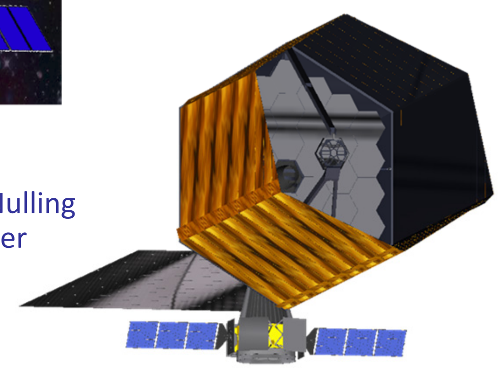
DAViNCI Dilute Aperture Visible Nulling Coronagraph Imager



TPF-I Terrestrial Planet Finder Interferometer



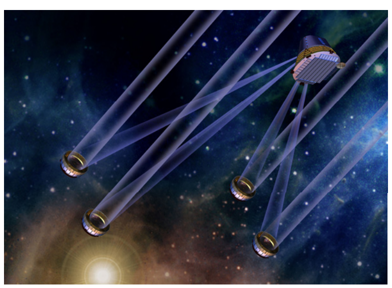
FKSI Fourrier-Kelvin Stellar Interferometer



ATLAST Advanced Technology Large-Aperture Space Telescope

Infrared Interferometer Concepts

- Wavelength range: 3-8 microns, 6-18 microns
- Cryogenic optics, diffraction limited
- Primary mirrors (0.5–2-m diameter) of berylium or silicon carbide
- Cryogenic deformable mirrors for wavefront correction
- Cryogenic delay-lines and fine-steering mirrors
- Mid-infrared single-mode fiber optics
- Cryocoolers for detectors
- Passive cooling of optics to 35–40 K
- Formation flying



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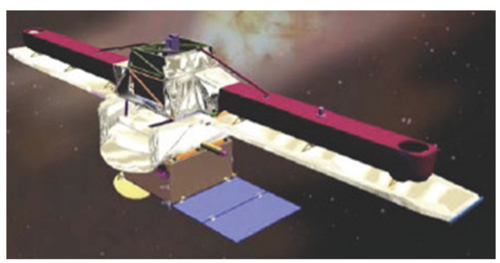
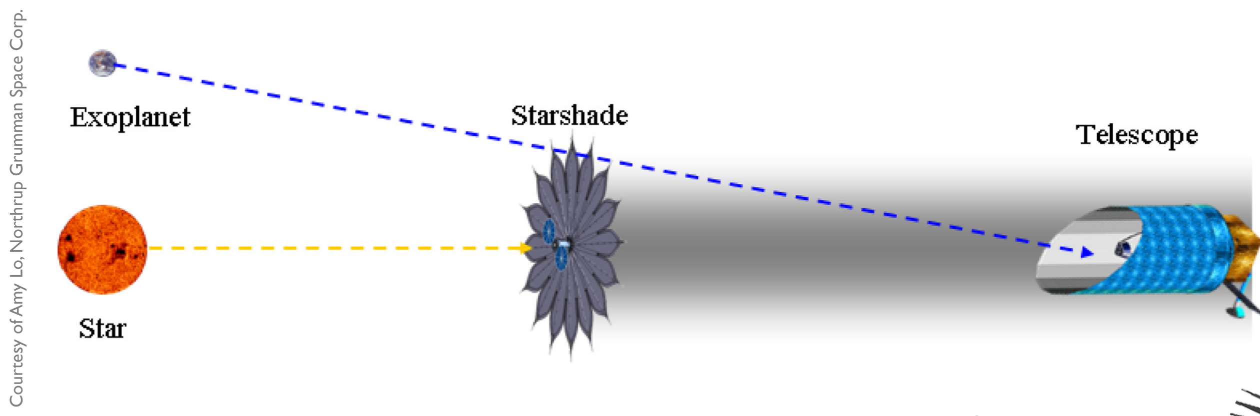
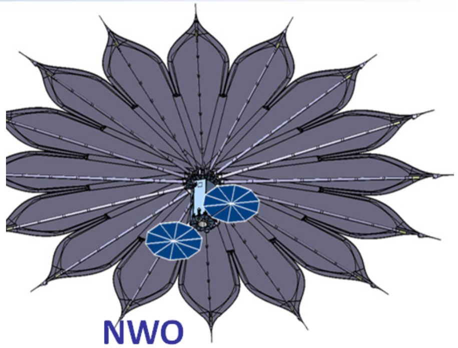


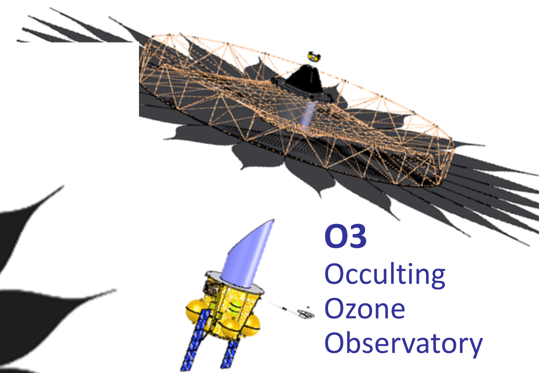
FKSI Fourier-Kelvin Stellar Interferometer

Research slowed or halted
Low-priority for NASA funding

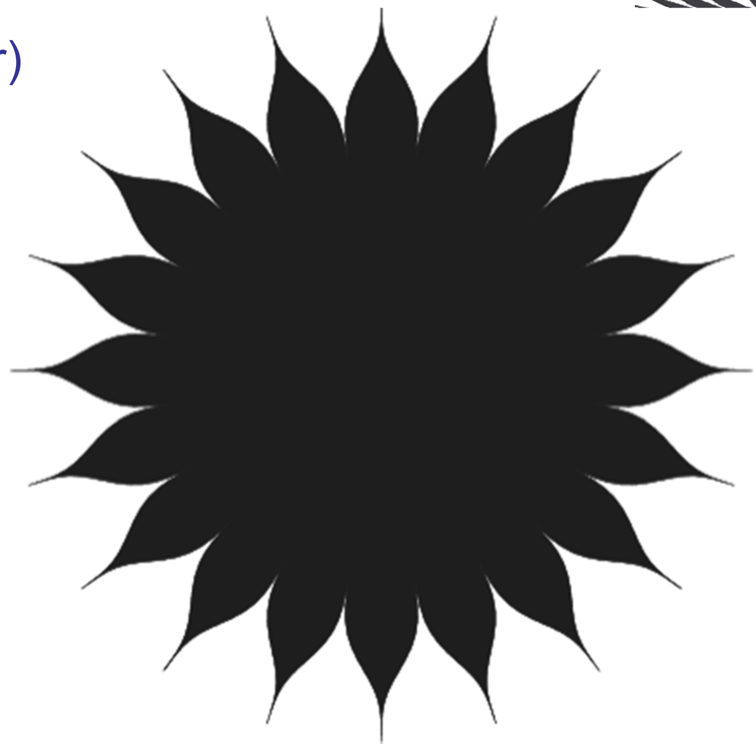
Starshades Concepts





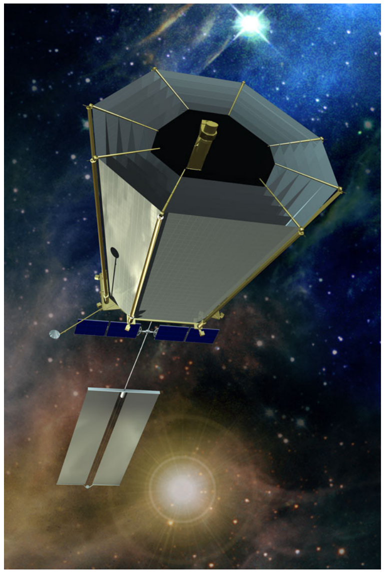


- Nominally 4-m (or larger) diffraction-limited primary mirror
- Mirror technology is not a driving concern
- Challenging technology is in the starshade itself and GN&C



Coronagraphs

ExoPlanet Exploration Program



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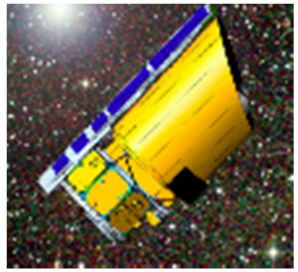

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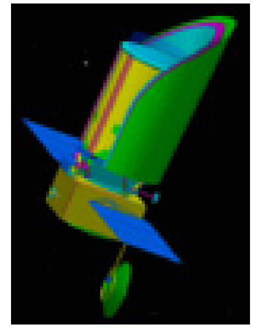
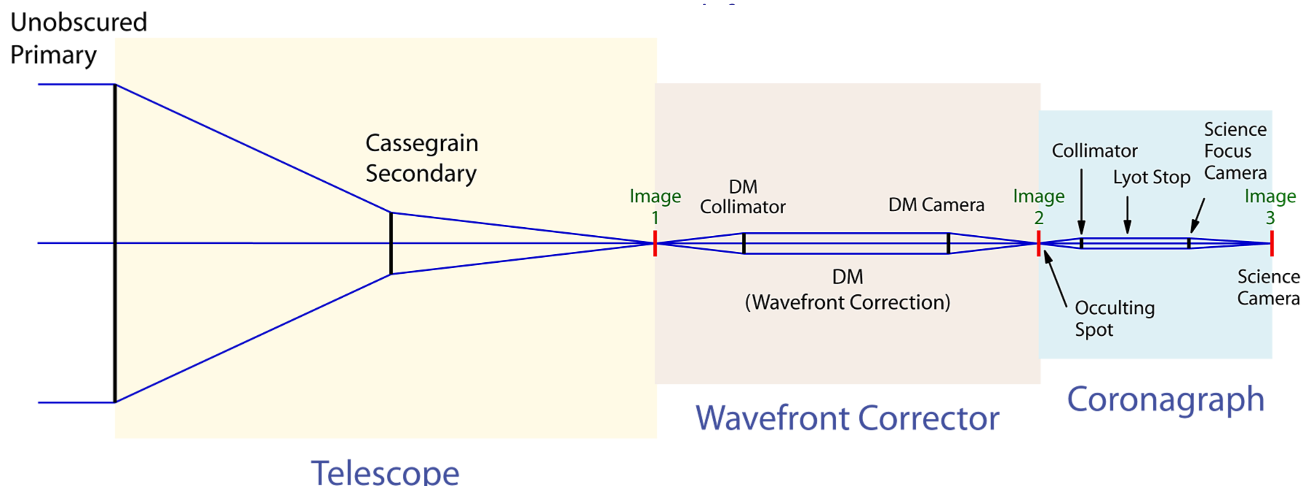
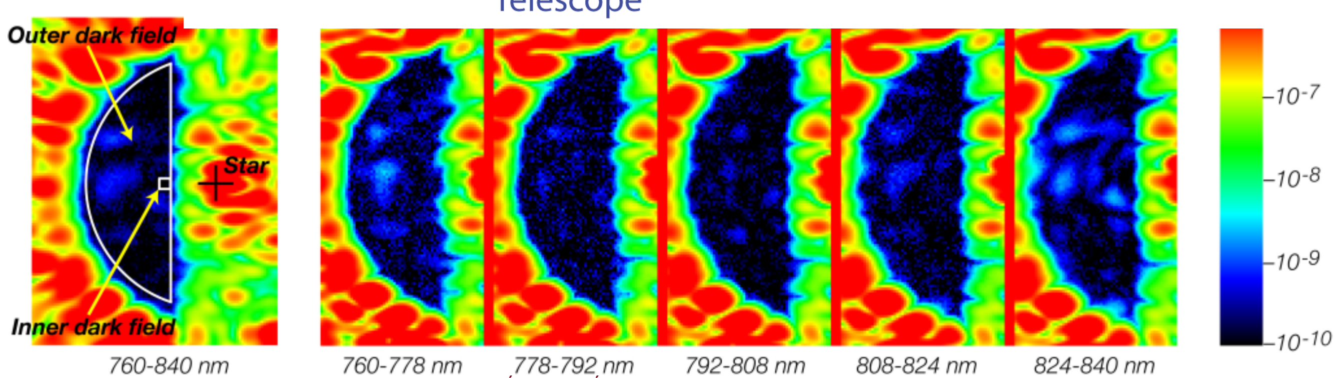
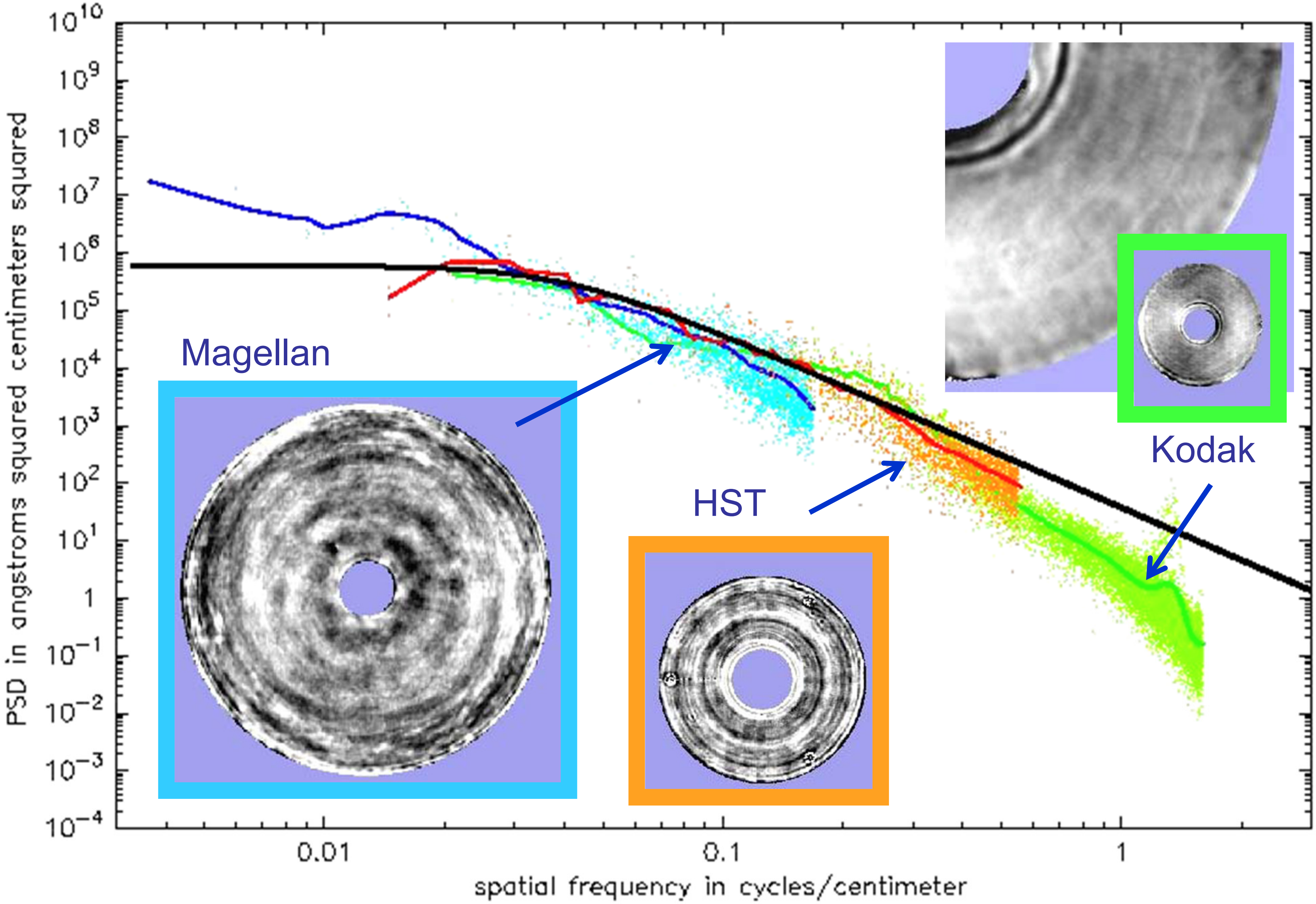


ACCESS Actively-Corrected





Primary Mirror: Surface Figure



Technology Demonstrator Mirror Requirements

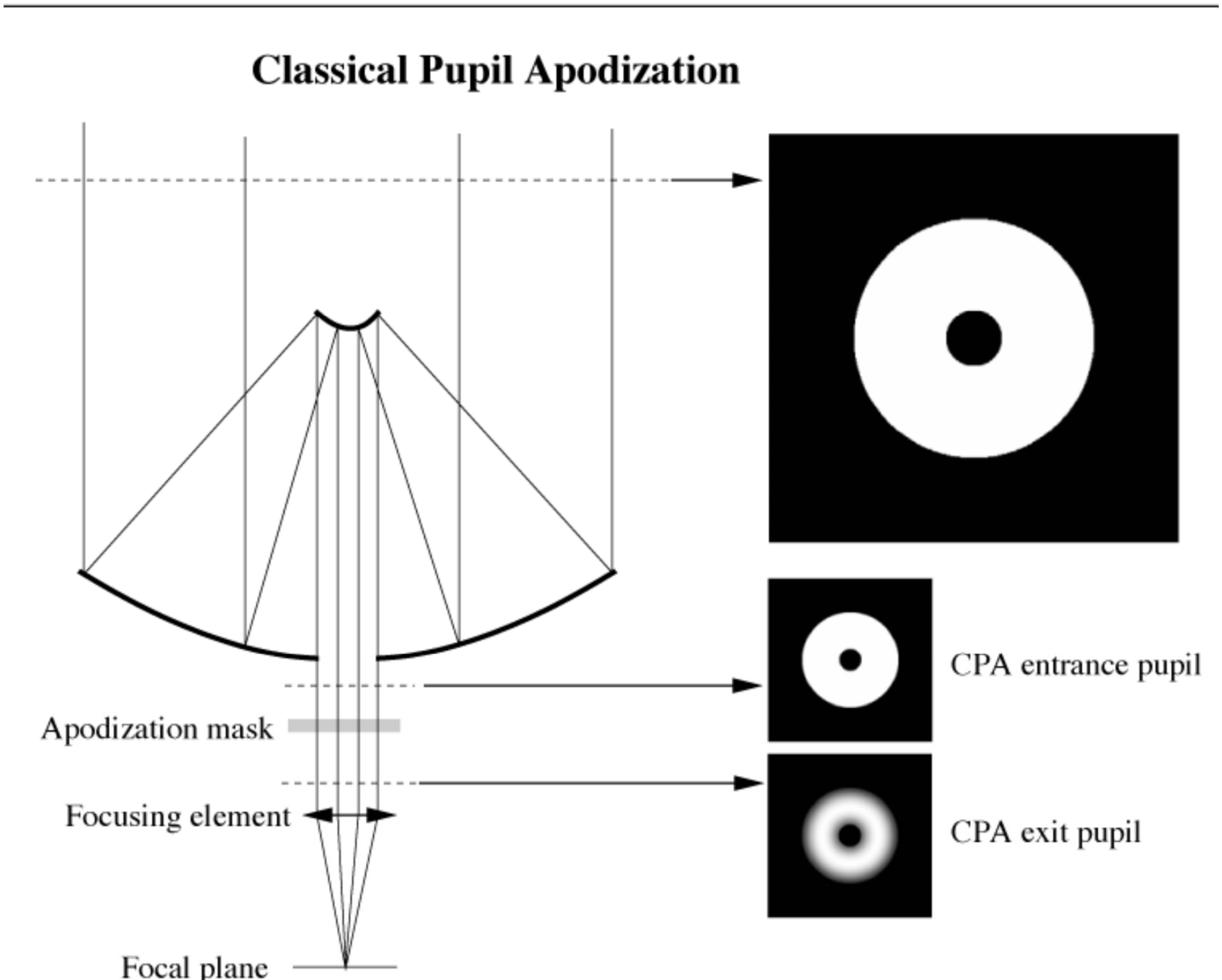
TDM Baseline Concept

- 1.9-m diameter, off-axis segment
- Surface errors < 5 nm rms in mid-spatial frequencies
- Areal density of 47.5 kg/m^2 (60 kg/m^2 required)
- Advanced waterjet lightweighted
- ULE glass
- On orbit PV quilting < 1mn

Not Required

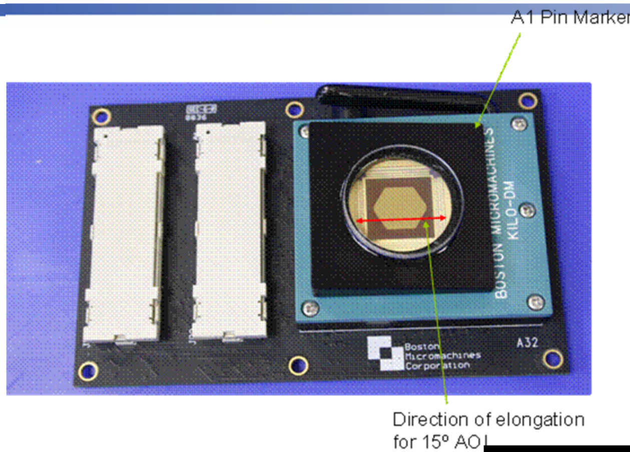
Parameter	Range	Requirement	Goal
SURFACE ERROR REQUIREMENTS			
Low Spatial Frequency	< 0.025 cycles/cm	10 nm rms	5 nm rms
Mid Spatial Frequency	0.025-0.5 cycles/cm	5 nm rms	2.5 nm rms
High Spatial Frequency	0.5-10 cycles/cm	1.4 nm rms	0.7 nm rms
Micro-roughness	> 10 cycles/cm	10 Å rms	5 Å rms
COATING RESIDUAL REFLECTANCE REQUIREMENTS			
Mid Spatial Frequency	0.025-0.5 cycles/cm	< 0.3% rms	≤ 0.1 % rms

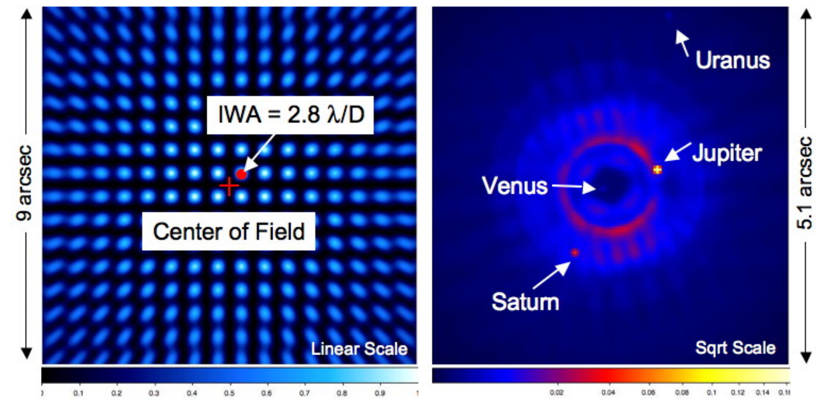
Phase-Induced Amplitude Apodization

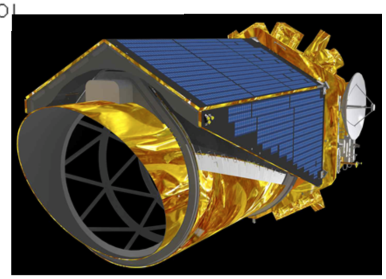


Visible Nulling Coronagraphs

ExoPlanet Exploration Program







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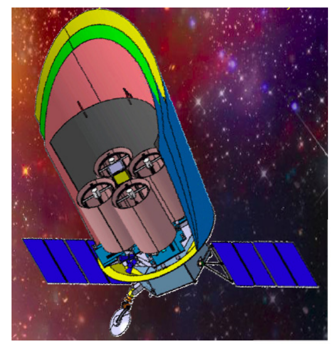

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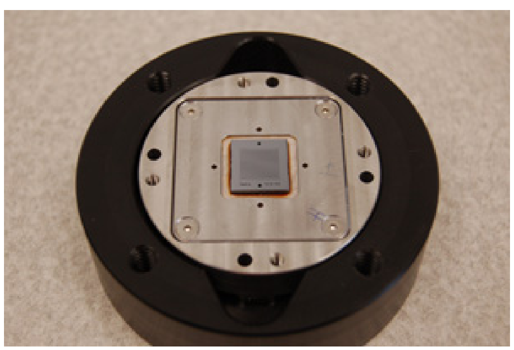
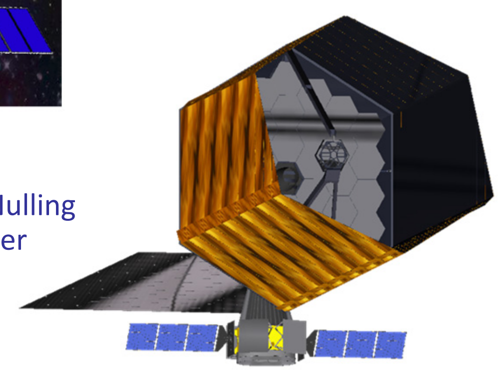
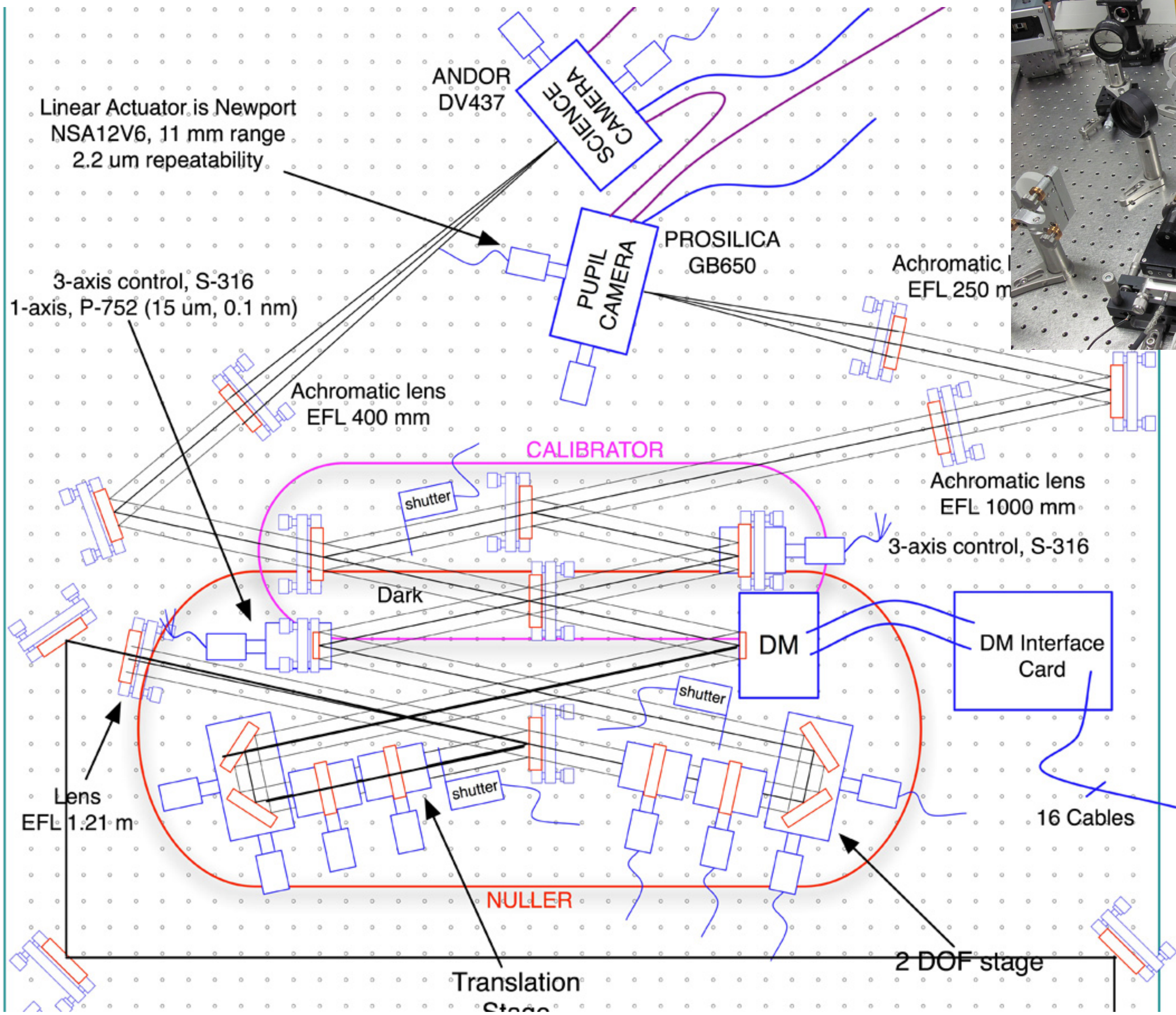


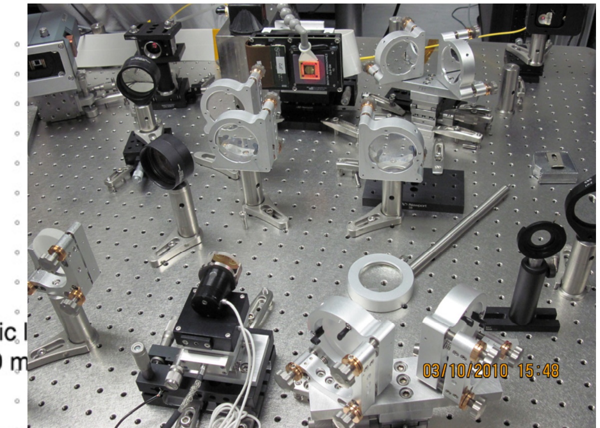


ATLAST Advanced Technology Large-Aperture Space Telescope

APEP Testbed at JPL

ExoPlanet Exploration Program





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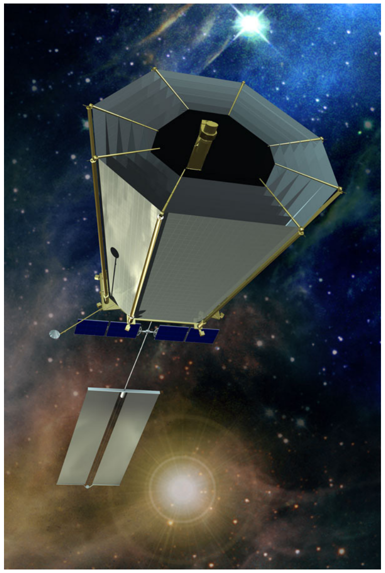
ExoPlanet Exploration Program



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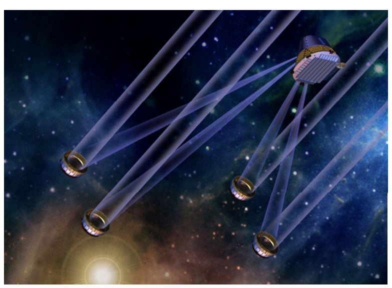

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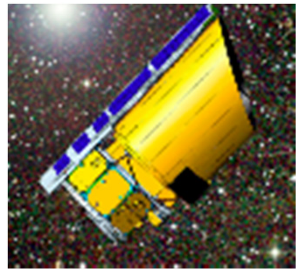

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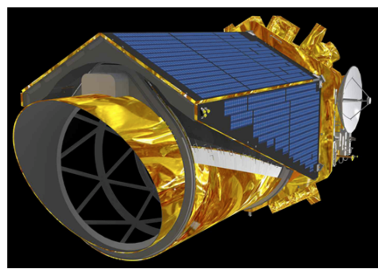

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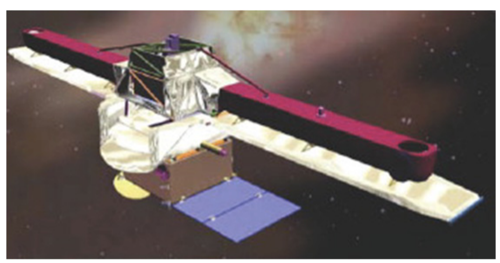

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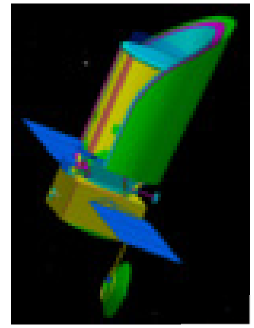

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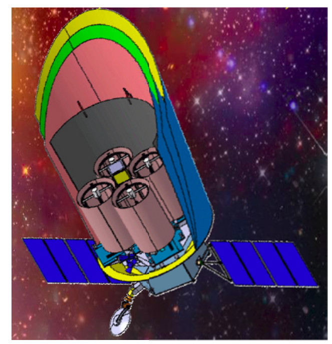

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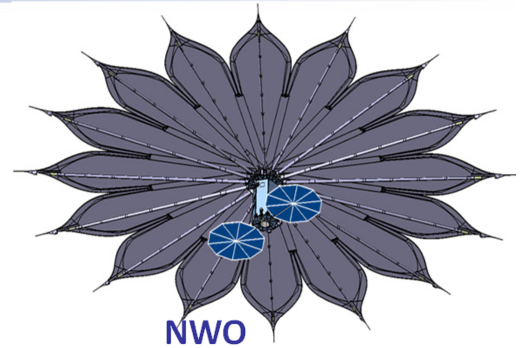

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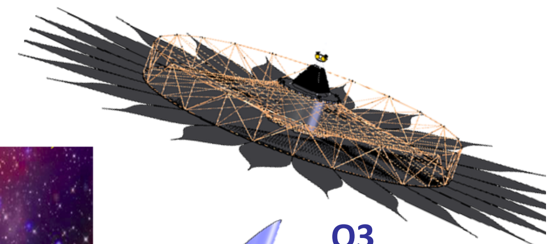

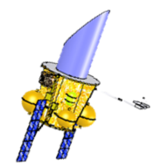

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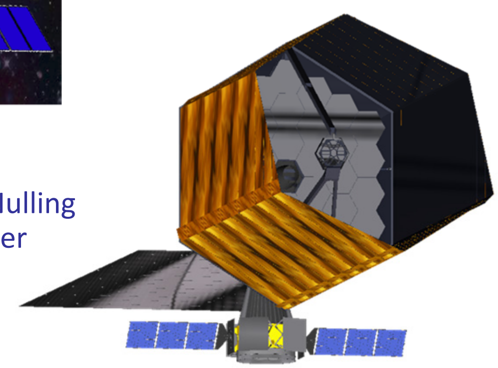


ATLAST Advanced Technology Large-Aperture Space Telescope

Design Trades

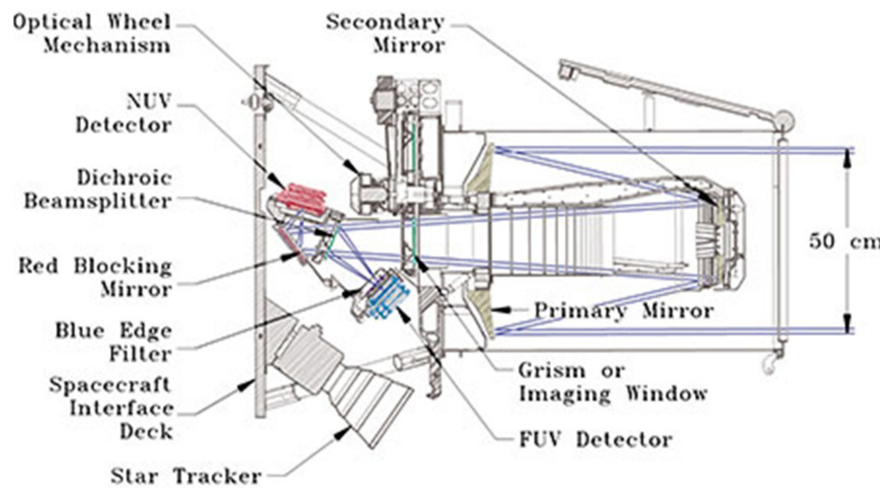
- Coronagraph
  - Starlight entering the telescope must be suppressed
  - Diffraction artifacts must be controlled or mitigated
    - Off-axis un-obscured aperture design
    - Coronagraphic masks
    - Deformable mirrors

- Visible Nulling Coronagraph
  - Similar constraints and requirements as above
  - Instrument is an interferometer
  - Well suited for use with segmented-mirror telescopes

- Starshade
  - Starlight never enters the telescope – no scattered light to suppress
  - Diffraction effects that must be controlled lie with the starshade
    - The telescope must simply be diffraction limited
  - Mirror technology is not a driving concern

UV/Optical and Exoplanet Mission?

Example: GALEX (2003–present)



The most cost-effective way to improve sensitivity for a UV telescope would be to develop better UV detectors and more efficient coatings – not by going to larger mirrors

Exoplanet missions need mirrors at **least** 4-m in diameter

A starshade design would not impose additional constraints on a UV telescope, other than adding navigator beacons or sensors

A coronagraph design typically requires an **unobscured**, **off-axis primary**, and polarization-preserving **multi-layer coatings**, thus imposing numerous additional requirements on the telescope

Summary of Technology Needs

ExoPlanet Exploration Program

Mission	Technology	Metric	State of Art	Need	Start	TRL6
NWTP	[1]Starlight suppression: visible	Design Contrast Contrast stability Bandwidth Inner working angle Model validation	4^{th} order mask 5×10^{-10} 10%, 760-840 nm 4 λ/D	 $< 1 \times 10^{-10}$ 1×10^{-11}/image 20%, at *V*, *I*, and *R* band 2λ/D – 3λ/D Errors predicted to 10^{-11}	2011	2016
NWTP	Detectors: Visible photon-counting	Design Format Quantum efficiency Noise properties Rad Hard	E2V CCD97 512 x 512 80%, 450-750 nm 0.1 e^-/pixel/frame clock-induced charge	CCD, APD or other 512 x 512 > 80%, 450-900 nm < 1 e^- read noise, or lower clock-induced charge > 20 kRad	2011	2020
NWTP	Deformable Mirrors	Format Design Resolution Env. testing	32 x 32, Xinetics PMN facesheet λ/10,000 rms Vacuum tested only	48 x 48 to 128 x 128 Both PMN and MEMs λ/10,000 rms Full environmental tests	2011	2020
NWTP	Observatory opto-thermo-mech control	Temperature stability Wavefront system stability	100 mK rms System dependent	< 10 mK rms 0.01–0.1 nm wavefront rms	2016	2020
NWTP	[2]Starshade deployment	mm rms of modes in error budget	Not yet demonstrated	< 0.1 mm rms in selected error terms	2011	2016
NWTP	[3]Starshade GN&C	Lateral alignment Separation distance	Not yet demonstrated	±0.7 m wrt tel. center 30,000 – 80,000 km	2011	2016
NWTP	Starlight suppression: Mid-infrared	Null depth Contrast Bandwidth Environmental tests	1×10^{-5}, 30% bwdth 1.65×10^{-8}; laser 30% at 10 μm Ambient	$< 1 \times 10^{-5}$ $< 1 \times 10^{-7}$ 50% 8 μm, 66% 15 μm Cryogenic	2011	2020
NWTP	[4]Formation Flying	Relative position Relative Pointing Degrees of Freedom Number of telescopes Separation Environment	5 cm rms 6.7 arcmin rms 5 2 telescopes 2-m Flat-floor, 1G	5 cm rms 6.7 arcmin rms 6 4 telescope, + combiner 15–400-m 0 G	2011	2020
NWTP	Optical Mirrors	Aperture Figure kg/m2 Coatings: polarization & uniformity	2.4 m HST 30 kg/m2	3 – 8 m HST <25kg/m2 300nm-1100nm	2011	2020

1. Contrast needed with coronagraphs or starshades to detect Earth-like exoplanets.
2. Subscale single-petal deployment.
3. Ground-based subscale demonstration.
4. A precursor flight-mission to demonstrate two-telescope formation flying.

2010 Phase 1: S2 Science Instruments

BEAM Engineering for Advanced Measurements
686 Formosa Avenue
Winter Park, FL 32789-4523
Nelson Tabirian (407) 629-1282
10-1-S2.02-8374 JPL
Achromatic Vector Vortex Waveplates for Coronagraphy

Boston Micromachines Corporation
30 Spinelli Place
Cambridge, MA 02138-1070
Paul Bierden (617) 868-4178
10-1-S2.02-8461 JPL
Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

Iris AO, Inc.
2680 Bancroft Way
Berkeley, CA 94704-1717
Michael Helmbrecht (510) 849-2375
10-1-S2.02-9446 GSFC
Picometer-Resolution MEMS Segmented DM

Bridger Photonics Inc.
112 East Lincoln
Bozeman, MT 59715-6504
Randy Reibel (406) 585-2774
10-1-S2.03-8200 JPL
Multi-Point Trilateration: A New Approach for Distributed Metrology

Vanguard Composites Group, Inc.
9431 Dowdy Drive
San Diego, CA 92126-4336
Steven Sherman (858) 587-4210
10-1-S2.03-8698 JPL
Carbon Fiber Reinforced, Zero CME Composites

L'Garde, Inc.
15181 Woodlawn Avenue
Tustin, CA 92780-6487
Roger Garrett (714) 259-0771
10-1-S2.03-9177 JPL
Thermally-Stable High Strain Deployable Structures

Trex Enterprises Corporation
10455 Pacific Center Court
San Diego, CA 92121-4339
Deborah Doyle (858) 997-9508
10-1-S2.04-9269 MSFC
Silicon Carbide Corrugated Mirrors for Space Telescopes

Summary

ExoPlanet Exploration Program

- There are several possible approaches to designing exoplanet missions
  - Coronagraphs
  - Interferometers
  - Starshades

- Wavefront sensing and control is the central concern, not mirror size
  - Starlight suppression with deformable mirrors
  - Thermal and structural stability
  - Metrology for sensing and control

- Diffraction-limited optical primary mirrors 4-m or larger are needed to detect Earth-like planets
  - Surface figure similar to HST required
  - Smaller primary mirrors can be used with aggressive coronagraph designs, but the stability toelrances become the driving concern
  - Stability tolerances of coronagraphs are greatly reduced when larger primaries are used in conjunction with 8^{th}-order masks

- Long term vision for large telescope development includes space-based segmented-mirror telescopes using actively-controlled glass segments or silicon carbide hybrid-mirror designs

References

- Eri Cohen and Tony Hull, “Selection of a mirror technology for the 1.8-m Terrestrial Planet Finder demonstrator mission,” Proc. SPIE 5494, p. 350-365 (2004).

- D. A. Content et al. “Engineering trade studies for the Terrestrial Planet Finder Coronagraph primary mirror,” Proc. SPIE 5867, 58670X (2005)

- S. B. Shaklan and J. J. Green, “Reflectivity and optical surface height requirements in a broadband coronagraph. 1. Contrast floor due to controllable spatial frequencies,” Appl. Opt. 45, 5143-5153 (2006)

- K. Balasubramanian et al. “Low-cost high-precision PIAA optics for high contrast imaging with exo-planet coronagraphs,” Proc. SPIE 7731, 77314U (2010)

Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

Government sponsorship acknowledged

ExoPlanet Exploration Program

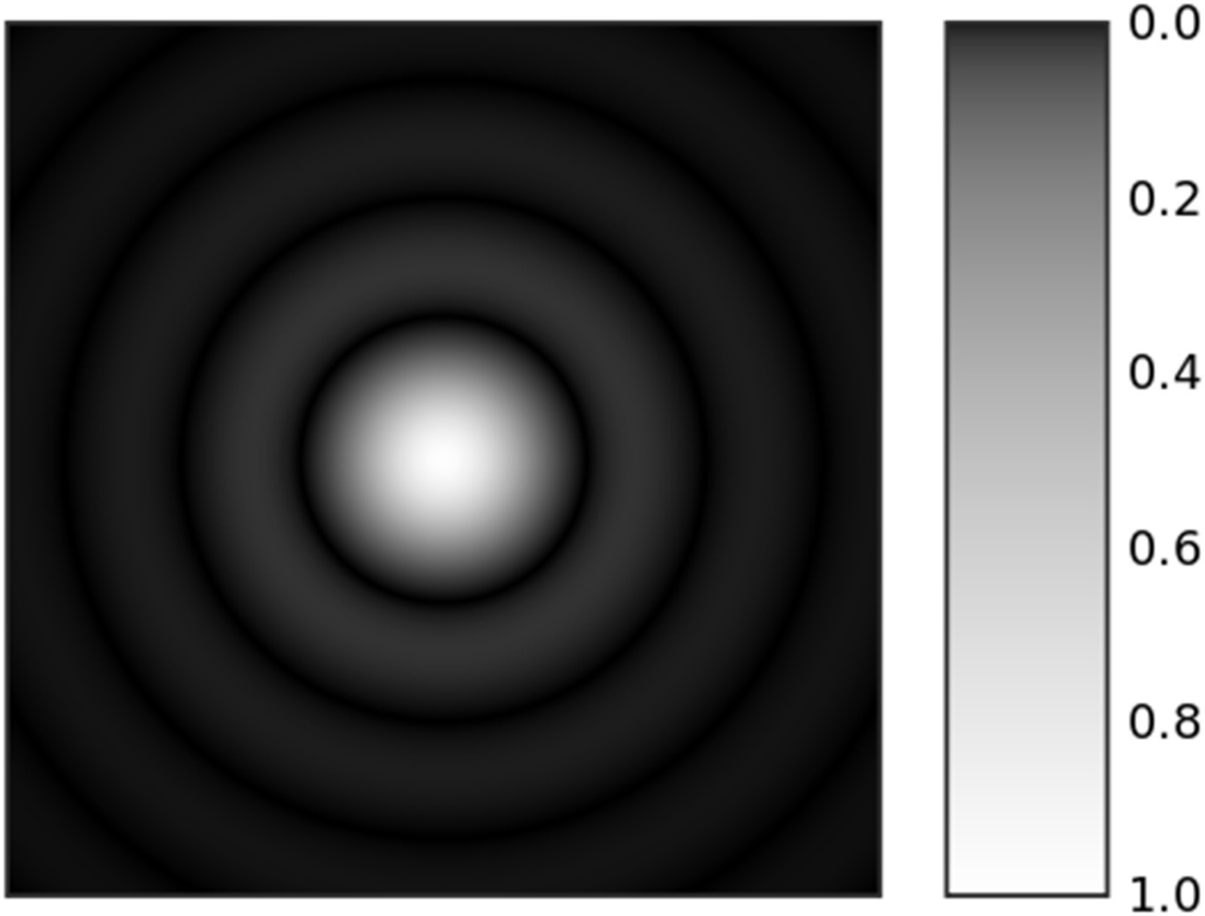
ExoPlanet Exploration Program

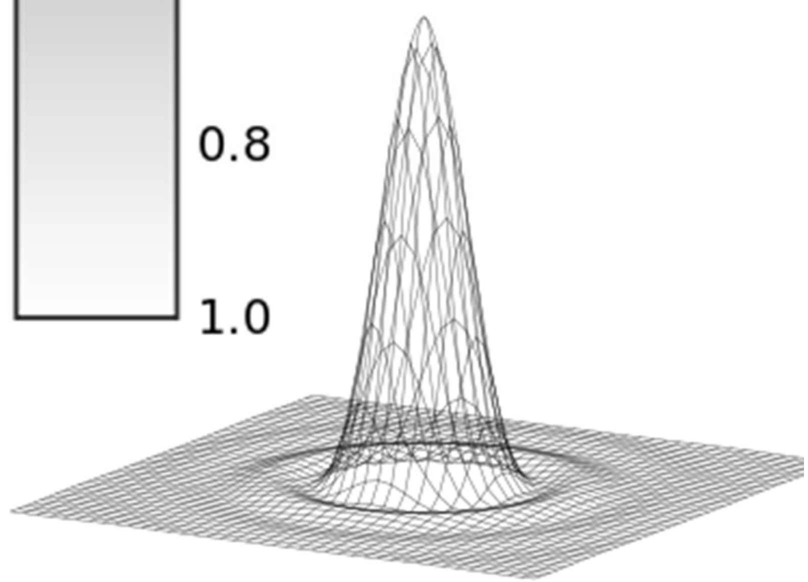
Backup

Overview

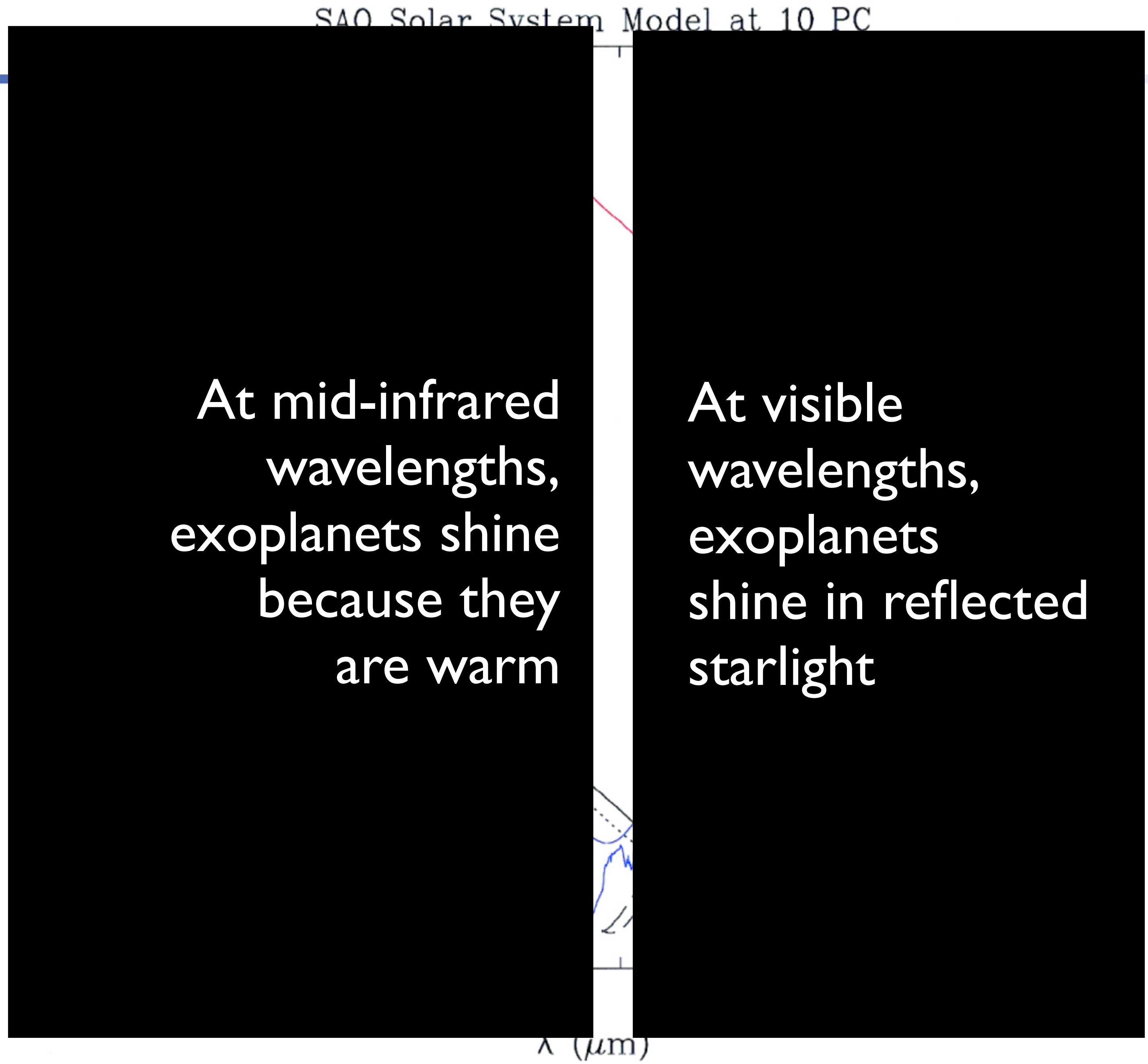
- Science objectives & Challenges
- Exoplanet Instrument and Architecture Designs
- UV/Optical Telescope
- Technology requirements
  - Mirror diameter
  - Surface roughness
  - Polarization properties
  - Thermal stability
- Coronagraphs
- Deformable mirrors
- Starshades
- A roadmap for mirror technology

Airy Disk





ExoPlanet Exploration Program



At mid-infrared wavelengths, exoplanets shine because they are warm

At visible wavelengths, exoplanets shine in reflected starlight

Example Requirements

ExoPlanet Exploration Program

Parameter	Design	Glass	Mirror Figure	Light-weighting	Coatings
TPF-C	Off-axis (f#2)		< 0.025 cycles/cm	10 nm rms	5 nm rms
TPF-C Lite (4-m)	Off-axis		0.025-0.5 cycles/cm	5 nm rms	2.5 nm rms
ACCESS (1.4-m)			0.5-10 cycles/cm	1.4 nm rms	0.7 nm rms
PECO (1.4-m)			> 10 cycles/cm	10 Å rms	5 Å rms
EPIC (1.4)			0.025-0.5 cycles/cm	< 0.3% rms	≤ 0.1 % rms
THEIA (4-m)					
NWO (4-m)					